Ocean Variability Effects on Underwater Acoustic Communications

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Award Number: N00014-06-1-0193
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LONG-TERM GOALS

This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high rate transceivers customized for coherent underwater acoustic communications.

OBJECTIVES

The research objective is to investigate the relationship between environmental fluctuations and the performance of coherent underwater acoustic communications at high frequencies (8-50 kHz) through experimental research and data analysis. High rate communication methods are to be developed based on acoustic propagation physics in the dynamic shallow water enviroment.

APPROACH

Several studies have been conducted in recent years that show correlation between high frequency acoustic fluctuations and environmental parameters. For example, effects of tidally driven temperature fluctuations on underwater coherent acoustic communications were studied for a carrier frequency of 18 kHz [1]. However, the relationship between environmental fluctuations and the performance of coherent underwater acoustic communications is not fully understood yet. On the other hand, underwater acoustic channels are challenging for coherent digital communications because of severe multi-path spread and limited bandwidth [2]. Furthermore, the variability of the ocean environment can cause fast fluctuations of acoustic channels and these fluctuations result in additional limitations on digital communications. To study the environmental fluctuation effects over an extended period, low complexity receivers that are able to accommodate fast channel fluctuations at high frequencies (8-50 kHz), including time-varying Doppler and fast phase variations, are needed. Therefore, our research emphasizes two efforts: acoustic communication measurements and high rate transceiver development for the underwater environment.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Ocean Variability Effects On Underwater Acoustic Communications**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware,College of Marine and Earth Studies,114C Robinson Hall,Newark,DE,19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

code 1 only

14. ABSTRACT

This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high rate transceivers customized for coherent underwater acoustic communications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

1) *KAM'08 Experiment.* PIs have participated in the Kauai Acoustic communication MURI experiment (KAM'08) from June 16 to July 02, 2008. During the joint efforts with the Marine Physical Laboratory (MPL), Scripps Institution of Oceanography, the Ocean Acoustics Laboratory, University of Delaware (UDel) provided acoustic measurement capabilities as well as environmental equipments in the three week at-sea experiment. The main objective of the UDel teams was to assess environmental variability effects on acoustic communications as functions of source depth, receiver depth, and communication range. High rate communications through use of spatial multiplexing and for moving platforms were also the UDel objectives. During the experiment, multiple deployments of two UDel tripod vertical line arrays (VLAs) were conducted when the environment was continuously monitored by the Thermistor String and the Waverider Buoy. Together with MPL's measurements obtained by multiple sources and two VLAs, abundant data have been collected for stated research in the area of high rate acoustic communications [3].

2) *Receiver Design for MIMO systems.* We have developed a time reversal combining/decision feedback equalization (TRC/DFE) structure for underwater acoustic multiple-input/multiple-output (MIMO) channels.

RESULTS

As reported in [4], we have developed a time reversal based receiver for single source communication system in the underwater channel. With the developed receiver, different types of PSK signals over an extended period in the Kauai experiment (KauaiEx) have been processed. The performance results demonstrate reliability of the reciever during dynamic sea surface states and different water column conditions. The time reversal based receiver now has been expanded to MIMO systems, where multiple element sources are used to drastically improve data rates for the underwater channel.

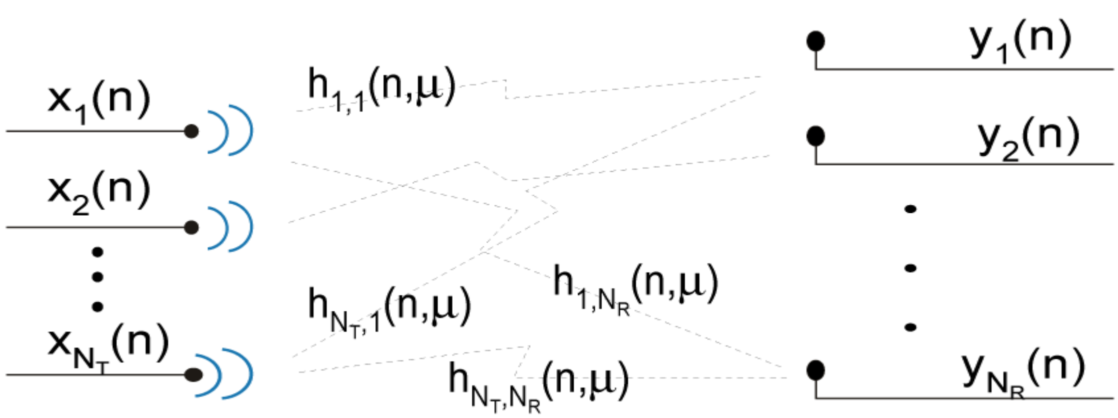

Figure 1. System model of a MIMO system.

As being bandwidth efficient in a rich scattering environment, MIMO techniques have been considered in the underwater channel. Based on the multichannel decision feedback equalizer (DFE) structure proposed in [5-7], various receivers for MIMO systems were developed with a focus on the utilization of error correcting codes [8-10]. In the highly dispersive underwater environment, the channel usually has a length of tens of symbols or more. The recovery of multiple information sequences from excessively long MIMO channels is often implemented at significant complexity if the multichannel DFE structure is used, for example in [8]. We seek to develope a low complexity alternative for the acoustic MIMO channel.

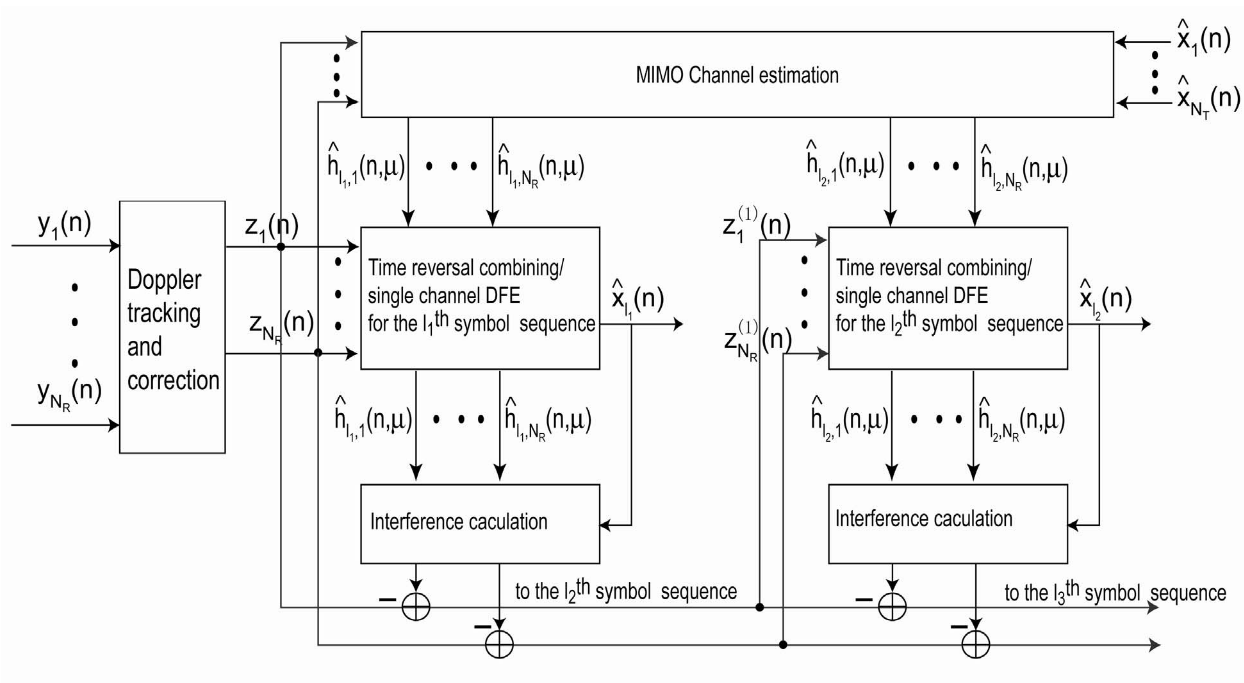

Figure 2. TRC/DFE structure with SIC for underwater acoustic MIMO channels.

Fig. 1 shows a MIMO system that is equipped with N_T transducers and N_R hydrophones in an underwater environment. At the *l*-th transducer at the source, an information symbol sequence $x_l(n)$ is modulated to carrier frequency f_c and transmitted. All N_T symbol sequences from N_T transducers are independent of each other. The effect of the transmission medium between the *l*-th transducer and the *m*-th hydrophone can be characterized by a time-varying channel impulse response (CIR) function, $h_{l,m}(n,\mu)$. Let $y_m(n)$ be the received baseband signal at the *m*-th hydrophone. Then it is the summation of all symbol sequences from all N_T transducers distorted by the channel. Therefore, the receiver has to compensate for both the intersymbol interference (ISI) caused by multipath and the co-channel interference (CCI) caused by transmitting multiple symbol sequences at the same time and at the same frequency band.

As shown in Fig. 2, our receiver is composed of phase tracking and correction, MIMO channel estimation, and time reversal combining and single channel DFE. Phase tracking and correction is used

to compensate for any other linear trend in the carrier phase offset. MIMO channel estimation is performed based on the phase-corrected signals and multiple estimated symbol sequences. The most recent channel estimates, $\hat{h}_{l,m}(n,\mu)$, are used in phase tracking and time reversal combining. Time reversal combining and single channel DFE are followed to demodulate the *l*-th symbol sequence. As mentioned, CCI exists because multiple symbol sequences share the use of the same channel and frequency band. In order to mitigate the CCI, serial interference cancellation can be incorporated into the TRC/DFE structure. The symbol sequences are demodulated in the order of the soft output SNR of the single channel DFE. As shown in Fig.3, the strongest symbol sequence, the l_1-th symbol sequence, is to be demodulated first. After the l_1-th symbol sequence is demodulated, interference resulted from it is removed. Then the second strongest symbol sequence is demodulated and the resultant interference is cancelled. The process repeats until all the symbol sequences are demodulated.

Note in [11-12], MIMO communications has been achieved by taking advantage of spatial diversity of the underwater acoustic channel, which is assumed time-invariant or slowly varying at the carrier frequency of 3-5 kHz. Although also based on the time reversal method, time reversal combining in [11-12] is performed based on channel probes or the known symbols at the beginning of the data packet.

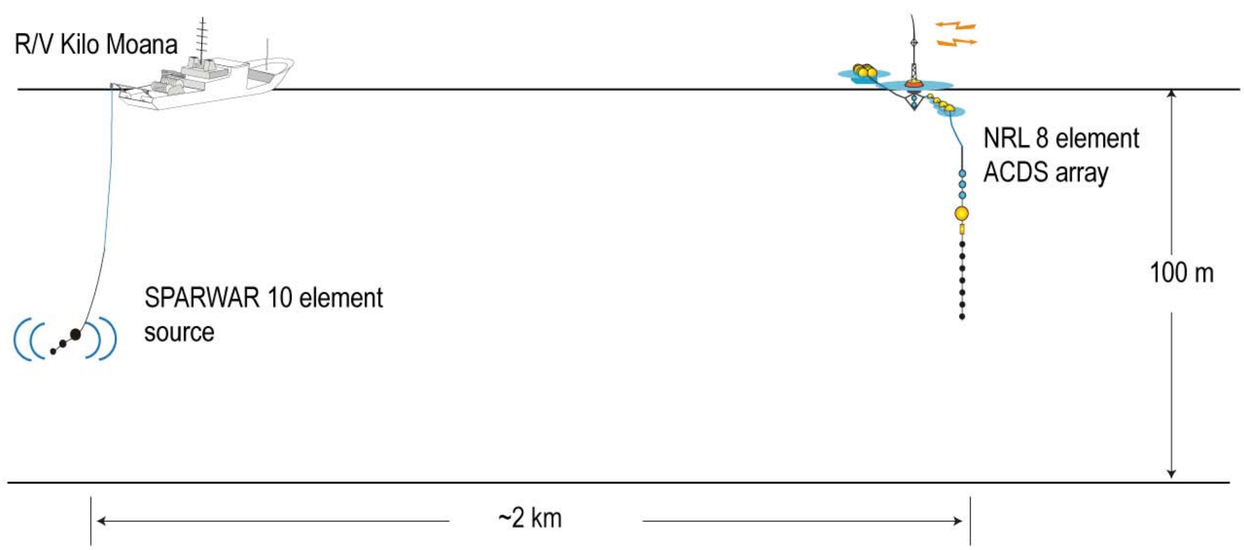

Figure 3. The Makai MIMO experiment.

The effectiveness of the receiver is shown by the experimental data obtained from MakaiEx. MakaiEx was conducted from Sept. 15 to Oct. 2, 2005, west off the Kauai Island, HI, to study high-frequency underwater acoustic communications [13]. During the MIMO experiment, a 10-element verctical MIMO source developed by Space and Naval Warfare Systems Center (SPAWAR) and an 8-element ACDS receiving array provided by Naval Research Laboratory (NRL) were deployed [14].

The ACDS array was deployed by the R/V Kilo Moana and drifted in the ocean. The top element of the ACDS array was about 20 m below the sea surface and the element spacing was about 2 m. The

sampling frequency of the ACDS array was 160 kHz. The MIMO source was hung from the deck of the R/V Kilo Moana. The spacing of the source elements was 2 m with the top element about 20 m below the sea surface. The source power level of each source element is 190 dB re 1 μPa at 1 m. During the MIMO transmissions, the R/V Kilo Moana maintained roughly a 2 km separation with the ACDS array.

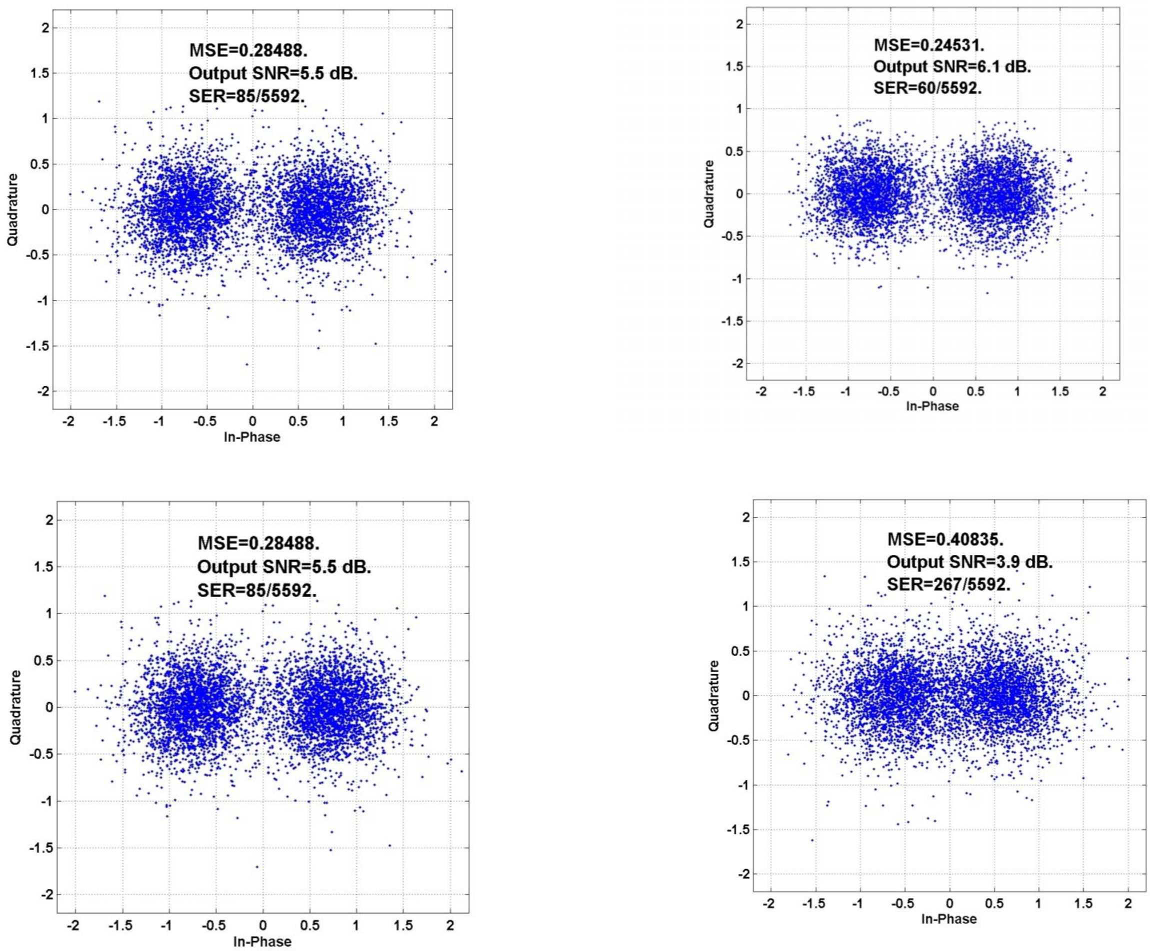

Figure 4. Scatter plot of four streams of BPSK sequences.
The aggregate data rate is 16 kbits/s. The overal BER is 0.019.

The water depth at the experimental site was about 100 m. The experimental setting is illustrated in Fig.3.

The carrier frequency of the analyzed communication data is $f_c = 37.5$ kHz and the symbol rate is $R = 4$ kilosymbols/s. The square-root raised cosine shaping filter is used with an excess bandwidth [15] of 75%. The communication data were in a form of packets. A 1248 symbol long preamble preceded the data packet. Pilot BPSK symbols were also intermittently inserted into the data to re-train the receiver. The pilot training overhead is about 30%. The total length of the packet was about 2.5 s.

Three types of source options were used, i.e., 1 transducer, 2 transducers, and 4 transducers, to transmit binary phase shift keying (BPSK) and 4 phase shift keying (QPSK) signals.

Using the obtained experimental data, we have shown that the achievable data rate can be increased 2 to 4 times using the same bandwidth as single source systems. For example, simultaneous transmission of four BPSK symbol sequences at an aggregate rate of 16 kbits/s can be demodulated with a bit-error-rate (BER) of 0.019 as shown in Fig. 4. Four QPSK MIMO sequences at an aggregate rate of 32 kbits/s may be demodulated with BER of 0.063 as shown in Fig.5. These data rates correspond to bandwidth efficiencies of 2.29 kbits/s/Hz and 4.57 kbits/s/Hz in the dynamic underwater channel.

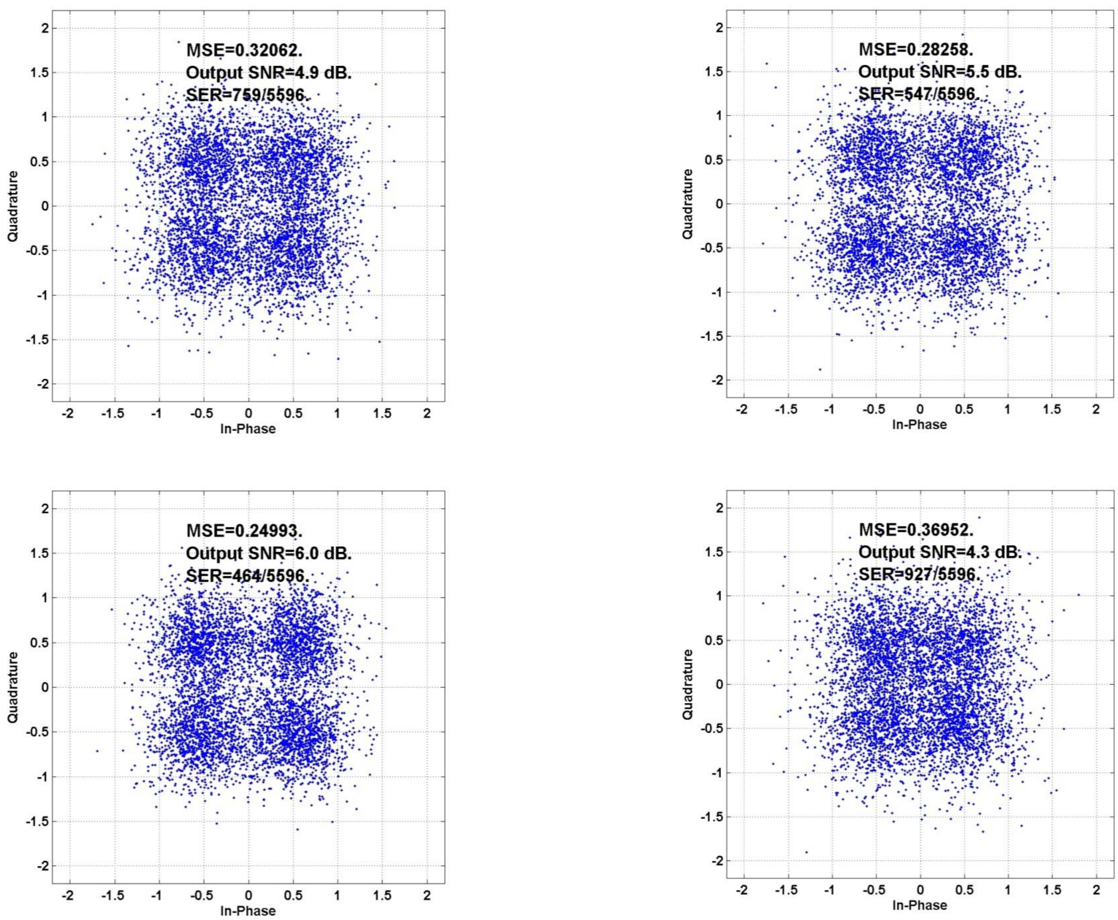

Figure 5. Scatter plot of four streams of QSK sequences.
The aggregate data rate is 32 kbits/s. The overal BER is 0.063.

IMPACT/APPLICATIONS

The developed receiver is a low-complexity structure for high data rate underwater digital communications at high frequencies. It can drastically improve data rates of underwater acoustic modems.

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